**Anadolu Orman Araştırmaları Dergisi**
**Anatolian Journal of Forest Research**

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# From Anatolian Plateau to American Plains: A transcontinental assessment of the EUMETSAT H SAF's new generation snow water equivalent product over Türkiye and the conterminous U.S.

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**ARTICLE INFO**
Received: 21/08/2023
Accepted: 12/10/2023
https://doi.org/10.53516/ajfr.1347158
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**ABSTRACT** **Research Article**

The main frame of this paper is to present the first validation results of the new generation hemi-spherical daily snow water equivalent (SWE) product of the EUMETSAT H SAF, namely, H65. It utilizes data from passive microwave radiometry sensors to estimate SWE. Operating at a suitable spatial scale, it offers insights into snow accumulation and melting dynamics, advancing satellite-based snow monitoring across diverse regions. The validation period covers the 2021 snow year, from January to March 2021, during which the dry snow conditions prevail. The validation is conducted in two distinct geographic regions, Türkiye, and the conterminous U.S. For Türkiye, the in-situ snow depth measurements provided by the Turkish State Meteorological Service are employed. On the other hand, the 1-km gridded SWE dataset of NOAA National Ice and Snow Data Center is used in the validation over the U.S. The validation results over Türkiye yields an overall RMSE of 39.27 mm, whereas it reads 15.19 mm for the U.S. These results indicate that the H65 SWE product complies with the product requirement thresholds for both flat (40 mm) and mountainous (45 mm) areas.

**Key Words**: Remote sensing of snow, EUMETSAT, H SAF, Snow water equivalent, H65, Passive microwave radiometry

## Anadolu Platosundan Amerika Ovalarına: EUMETSAT H SAF'ın yeni nesil kar suyu eşdeğeri ürününün Türkiye ve ABD üzerindeki kıtalararası değerlendirmesi

**ÖZ**

Bu makalenin ana çerçevesi, EUMETSAT H SAF'ın yeni nesil yarı küresel günlük kar suyu eşdeğeri (KSE) ürünü olan H65'in ilk doğrulama sonuçlarını sunmaktır. Ürün KSE'yi tahminlemek için pasif mikrodalga radyometri sensörlerinden gelen verileri kullanmaktadır. Uygun bir mekânsal ölçekte çalışan bu ürün, kar birikimi ve erime dinamikleri hakkında içgörüler sunarak çeşitli bölgelerde uydu tabanlı kar izlemeyi geliştirmektedir. Doğrulama dönemi, kuru kar koşullarının hüküm sürdüğü 2021 Ocak ayından Mart 2021'e kadar olan 2021 kar yılını kapsamaktadır. Doğrulama, Türkiye ve ABD olmak üzere iki farklı coğrafi bölgede gerçekleştirilmiştir. Türkiye için Meteoroloji Genel Müdürlüğü tarafından sağlanan yerinde kar derinliği ölçümleri kullanılmıştır. Öte yandan, NOAA Ulusal Buz ve Kar Veri Merkezi'nin 1 km'lik hücreli SWE veri seti ABD üzerindeki doğrulamada kullanılmıştır. Türkiye üzerindeki doğrulama sonuçları 39,27 mm'lik genel bir RMSE verirken, ABD için bu 15,19 mm olmaktadır. Bu sonuçlar, H65 SWE ürününün hem düz (40 mm) hem de dağlık (45 mm) alanlar için ürün gereksinim eşiklerine uyduğunu göstermektedir.

**Anahtar Kelimeler:** Karın uzaktan algılanması, EUMETSAT, H SAF, Kar suyu eşdeğeri, H65, Pasif mikrodalga radyometrisi

*Citing this article:*
Kuter, S., Karaman, Ç.H., Akpınar, M.B., Akyürek, Z., 2023. From Anatolian Plateau to American Plains: A transcontinental assessment of the EUMETSAT H SAF's new generation snow water equivalent product over Türkiye and the conterminous U.S. Anatolian Journal of Forest Research, 9(2), 33-40.

## 1. Introduction

Snow cover, a vital component of the Earth's cryosphere, exerts profound influences on the planet's climate and water cycles, yielding far-reaching consequences. On an annual basis, seasonal snow blankets a substantial proportion of the Earth's surface, encompassing approximately 31% of the total land area and 40% of the terrestrial surface in the Northern Hemisphere (Hall et al., 1995; Breen et al., 2023). This extensive coverage significantly contributes to the Earth's albedo, reflecting a large portion of incoming solar radiation back into space, thereby cooling the planet (Tekeli et al., 2005). Additionally, snow acts as an insulating layer, preserving soil moisture and protecting vegetation and ecosystems from extreme cold temperatures during winter (Kuter et al., 2018).

Nevertheless, the spatial extent of this snow cover exhibits considerable intra- and inter-annual fluctuations (Wang et al., 2018). Factors such as atmospheric circulation patterns, regional climate variability, and natural climate oscillations contribute to the variability in snowfall from year to year and even within a single season. This dynamic nature of snow cover can have significant implications for various sectors, including agriculture, hydrology, and transportation, as it affects water availability, flood risks, and accessibility in different regions.

Recent investigations have ascertained a discernible declining trend in the global coverage of snow, primarily attributable to the effects of a warming climate (Pulliainen et al., 2020; Wang et al., 2018). The ongoing rise in global temperatures is leading to alterations in precipitation patterns, shifting the rain-snow transition zones towards higher elevations, and causing earlier snowmelt in many regions. This reduced snow cover not only affects the environment but also has socio-economic implications, including potential impacts on winter tourism and water resources management. Notably, these alterations in snow cover extent manifest substantial variations across diverse geographical regions (Brown and Mote, 2009). Local and regional factors, such as latitude, altitude, proximity to oceans, and topography, play crucial roles in determining the response of snow cover to climate change. Some regions, particularly high-altitude mountainous areas, may experience amplified reductions in snow cover, leading to altered water availability and potential ecological consequences (Viviroli et al., 2007).

Space-based instruments operating at visible and microwave frequencies serve as valuable tools for globally retrieving two significant snow parameters: *snow cover extent* (SCE) and *snow water equivalent* (SWE). SCE denotes the spatial coverage of snow and is further classified into two subcategories: *i*) binary snow cover, indicating snow presence or absence (i.e., snow/no snow), and *ii*) sub-pixel snow cover, quantifying *fractional snow-covered area* (fSCA) by representing the percentage of snow within a pixel's footprint (Kuter et al., 2022). Binary snow cover is commonly derived from optical data using image thresholding techniques, where pixel values above a specific reflectance threshold are considered snow-covered, while values below the threshold are classified as snow-free. This binary representation facilitates the study of SCE over large regions. Sub-pixel snow cover estimation also leverages multispectral optical remote sensing data. However, by this approach, the fSCA within each pixel can be estimated through the analysis of the spectral characteristics of different land cover types and snow (Painter et al., 2003; Painter et al., 2009). This information offers a more detailed and continuous representation of snow cover's spatial distribution, enhancing our understanding of snow dynamics, particularly in complex terrain and regions with mixed land cover types.

Conversely, the estimation of SWE involves active/passive microwave techniques (Pulliainen and Hallikainen, 2001; Saberi et al., 2020), which exploit the interaction between microwaves and the snowpack's physical properties to accurately determine the amount of liquid water content present within the snowpack (i.e., the depth of water that would result if the entire snowpack were to melt instantaneously). This data is crucial for water resource management, flood forecasting, and monitoring ecosystem health reliant on snowmelt. This fundamental parameter bridges the gap between snow depth and its actual water content, providing vital insights into water availability during the snowmelt season (Pulliainen, 2006; Margulis et al., 2019). Accurate estimation of SWE is of utmost importance for water managers, hydrologists, and policymakers, as it enables effective planning for agricultural needs, hydropower generation, and ecological sustainability.

Moreover, SWE monitoring plays a critical role in flood forecasting and drought management. The gradual release of stored water from snowpacks can lead to spring flooding, potentially causing damage to infrastructure and posing risks to communities in flood-prone areas. Conversely, insufficient SWE may indicate potential drought conditions, which can have severe impacts on water resources, agriculture, and ecosystems. By harnessing this essential information, communities can proactively prepare for both water abundance and scarcity, reducing the risks associated with extreme weather events (Pulliainen and Hallikainen, 2001; Takala et al., 2011).

The new generation daily operational SWE product H65 provided within the *Support to Operational Hydrology and Water Management* (H SAF, https://hsaf.meteoam.it/) program of the *European Organisation for the Exploitation of Meteorological Satellites* (EUMETSAT, https://www.eumetsat.int/) is the successor of the H13 (H-SAF_H13_PUM, 2018), which has a Pan-European coverage. The H65 product is a hemispherical SWE product that spans the entire Northern Hemisphere with a nominal horizontal resolution of 0.25°.

The primary objective of this article is to present the first validation results of the H65 SWE product. The validation efforts are mainly divided into two distinct geographic areas and include two separate reference datasets. The first part is conducted in Türkiye by using in-situ *snow depth* (SD) measurements obtained from the ground observation network of the *Turkish State Meteorological Service* (TSMS). The second part of the validation efforts takes place over the conterminous U.S. The reference SWE data used in this part is acquired from the *Snow Data Assimilation System* (SNODAS) data products provided by the *National Snow and Ice Data Center* of the *National Oceanic and Atmospheric Administration* (NOAA). Through these two individual and spatially exclusive validation studies, the article aims not only to illustrate how practical and effective these snow products are in actual situations, but also to highlight the significant contributions of the EUMETSAT H SAF program in this particular field.

The remaining part of this manuscript is organized as follows: In Section 2, we introduce the H65 SWE product and the two reference datasets employed during the validation. Additionally, we describe the basic methodology followed in the validation. Section 3 briefly presents the results and discussions. Finally, in Section 4, we provide conclusions, along with outlining potential future directions.

## 2. Materials and Methods

This section presents the materials and methods used in the validation of the H65 SWE product over Türkiye and the United States. We describe the H65 SWE product and outline the reference datasets employed for validation. The methodology, data collection/processing, and employed statistical metrics are detailed, providing a comprehensive understanding of our validation approach.

### 2.1 Description of the H65 SWE product

The daily operational H65 SWE product (https://hsaf.meteoam.it/Products/ProductsList?type=snow) bears substantial resemblance to product H13, although exhibiting a noteworthy augmentation in its geographical scope, which now extends exclusively to the Northern Hemisphere. Unlike H13, which adopts the conventional latitude-longitude grid, H65 employs the *Equal Area Scalable Earth* (EASE) grid version 2.0. The latter's specific implementation is based on Lambert's equal-area, azimuthal projection, defined by the EPSG code 6931. The EASE 2.0 grid in H65 comprises a grid size of 720 x 720 pixels, with each pixel spanning a spatial extent of 25 km x 25 km. Remarkably, this resolution is comparable to that of H13, which stands at 0.25°. The H65 image on 27 January 2021 is shown in Figure 1.

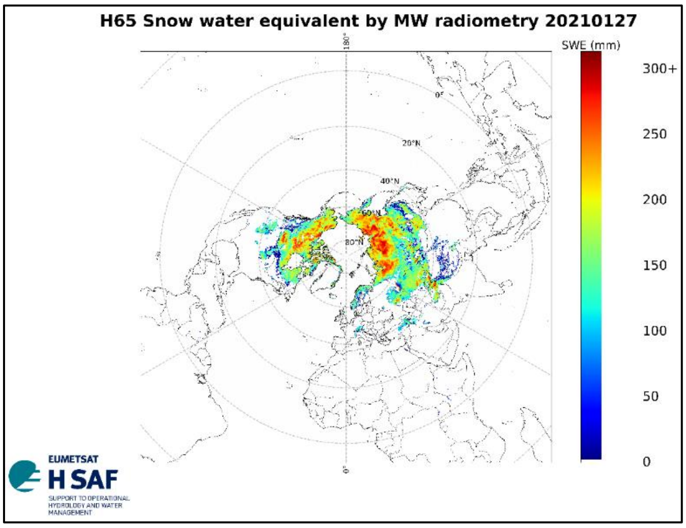


**Figure 1.** The H65 SWE product on 27 January 2021 in EASE-Grid 2.0 representation

The process of deriving H65 SWE values hinges upon the utilization of passive microwave radiometer data, specifically acquired from the *Special Sensor Microwave Imager/Sounder* (SSMI/S) satellites (NSIDC, 2023). These satellites are integral components of the *Defense Meteorological Satellite Program* (DMSP) and constitute an essential aspect of NASA's Pathfinder Program. The retrieval algorithm examines the variations in brightness temperature 19 GHz and 37 GHz vertically polarized channels caused by diverse snow characteristics such as depth, density, and grain size.

The H65 product derives its foundation from the ESA GlobSnow SWE retrieval approach, as documented by Takala *et* al. (2011). This methodology merges satellite passive microwave radiometer measurements with data from ground-based synoptic weather stations, utilizing Bayesian non-linear iterative assimilation. Notably, the GlobSnow approach is effective primarily in areas with relatively flat and non-mountainous terrain. However, the H65 product overcomes this limitation by incorporating gap-filling techniques specifically tailored for mountainous regions, as outlined in the study conducted by Sorman and Beser (2013). Consequently, flat product (produced by Finish Meteorological Institute) and mountain product (produced by Turkish State Meteorological Service) are merged based on a mask (cf. Figure 2) to form a unified product.

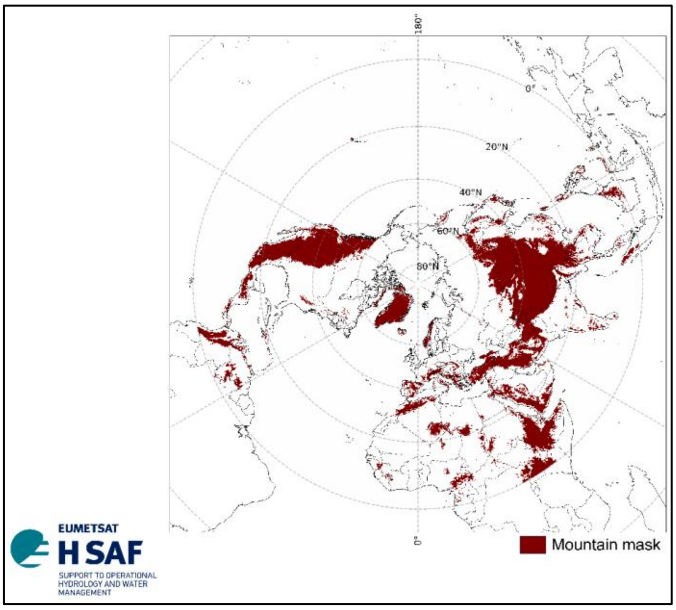


**Figure 2.** Mountain mask for H65 product

### 2.2 Reference datasets employed in the validation

#### 2.2.1 In-situ snow depth data from TSMS

The validation process of the H65 product is accomplished by comparing it with *snow depth* (SD) measurements obtained from the ground observation network of TSMS. The validation spans the period from 1st of January 2021 to 31st of March 2021.

To ensure data quality, all available station observations acquired from *automated weather observing system* (AWOS) and *snowpack analyzer* (SPA) stations within the TSMS network underwent a thorough process of revision, correction, and filtering, aimed at minimizing any errors or inaccuracies present in the observation data. Due to various technical factors, such as inadequate maintenance, sensor malfunctions, interference from vegetation (e.g., grass), and other related issues, a subset of monitoring stations within our validation study may not be operationally reliable. Consequently, rigorous quality assurance and filtering procedures, which entail meticulous assessment and validation of individual station data, including cross-referencing data from nearby stations, are undertaken. These procedures, executed by a custom MATLAB code, are designed to eliminate data of suboptimal quality or data that is missing before the validation process commences. After the filtering process, 62 AWOS stations and 6 SPA stations were selected, resulting in a subset of 68 stations with 1184 reliable SD measurements. The locations of AWOS and SPA stations involved in the validation are shown in Figure 3.

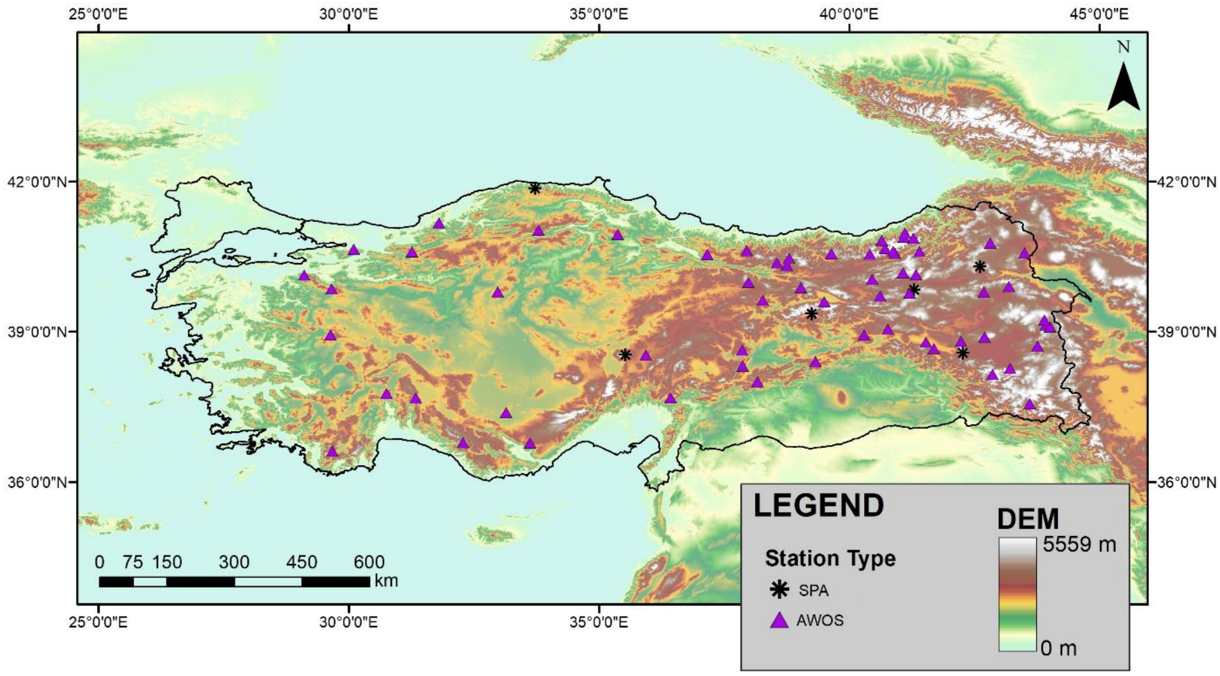


**Figure 3.** The locations of the AWOS and SPA stations used in the validation of H65 over Türkiye

These SD measurements were subsequently transformed into SWE values. When converting the in-situ snow SD measurements to SWE, the process involves using monthly average density values. These density values were acquired in previous field campaigns using snow pit measurements (Sorman and Beser, 2013), and they typically range from 0.25 g/cm³ to 0.30 g/cm³.

In the process of validation, in-situ measurements are individually compared with the corresponding 25 x 25 km² footprint of the H65 SWE product. Each in-situ measurement location's elevation is then compared with the median elevation value of the pixel where the measurement falls within its spatial extent. To ensure the validity of the comparison, weather stations with an elevation difference exceeding 400 meters from the pixel's median elevation value are excluded from the validation analysis. Since the H65 SWE product is specifically designed for dry snow conditions, the validation period is strategically chosen as January to March, a period where such conditions are prevalent.

### 2.2.2 The SNODAS SWE dataset over the conterminous U.S.

The evaluation of the H65 product's performance during the same period is also conducted using the daily 1-km gridded dataset available from 28$^{th}$ of September 2003 to present. The dataset encompasses snowpack properties, including SD and SWE, and originates from the NOAA *National Weather Service's National Operational Hydrologic Remote Sensing Center* (NOHRSC) *SNOw Data Assimilation System* (SNODAS) (https://nsidc.org/data/g02158/versions/1).

SNODAS integrates methods to ingest and downscale data from numerical weather prediction models, along with employing a physically-based, spatially-distributed energy and mass-balance snow model for simulating snow cover. Moreover, SNODAS incorporates procedures to assimilate diverse observations of snow-covered area and SWE from sources such as satellites, airborne platforms, and ground-based measurements (Webster and Fetterer, 2004). These estimates are instrumental in supporting hydrologic modeling and facilitating comprehensive analyses of snow-related phenomena (Webster and Fetterer, 2004). The assimilation methodology and other technical details regarding the dataset are provided in Carroll et al. (2001). The spatial domain of the 1-km gridded U.S. SWE data is shown in Figure 4.

As indicated in the product user manual (Webster and Fetterer, 2004), in some high-elevation areas, there are inaccurately high SWE values due to various factors, specifically, certain regions experience unrestricted snowpack growth in the SNODAS model because of insufficient mechanisms for snow removal, with sublimation being the sole means of loss. However, the model's sublimation processes might not effectively constrain the boundless snow accumulation. Additionally, these elevation zones lack observational data, and the SNODAS assimilation process does not incorporate mechanisms to regulate SWE estimates in these areas. Thus, these extreme SWE values are filtered and excluded from the analysis by the MATLAB subroutine specifically developed for the validation process. The reference SWE value for each valid H65 pixel is calculated by taking the mean of the 1-km U.S. SWE pixels inside the footprint of that H65 pixel.


**Figure 4.** The spatial coverage of the U.S. SWE dataset used in the validation

### 2.3 Evaluation metrics

The validation results over Türkiye and the U.S. are expressed in terms of the *root-mean-squared error* (RMSE), as given by the following expression:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(\mathrm{SWE_{Ref}} - \mathrm{SWE_{H65}})^2}{N}} \quad (1)$$

where $SWE_{Ref}$ indicates either the in-situ SWE value at the corresponding location of ground station, or the SWE value obtained from the U.S. SWE dataset. $SWE_{H65}$ is the SWE of the associated pixel in the H65 product, and *N* denotes the total number of observations.

In addition to RMSE, the validation outcomes are visualized through scatter plots. These plots display the average estimated SWE by H65 within specific 25 mm SWE intervals. These averages are compared against the corresponding mean of reference SWE values within the same 25 mm SWE intervals for each validation area. The plots also include standard deviation bars for context.

## 3. Results

### 3.1 Validation results over Türkiye

The validation results for the H65 product obtained from the in-situ SD data over Türkiye for the 2021 water year are given in Table 1. The characteristics of the SSMI/S instrument's penetration lead to distinct effects in the retrieval of SWE, causing overestimation in the case of shallow snow and underestimation for deeper snow accumulations. When the ground truth SWE surpasses the 150 mm mark, a consistent trend of underestimation becomes noticeable, exemplified in Figure 5 for the SWE range of 175-200 mm. This pattern is a typical behavior observed in the algorithm due to the saturation of radiometer signals with high SWE values. While an overestimation is apparent within the 150-175 mm SWE range, it's important to exercise caution in drawing definitive conclusions due to the limited availability of in-situ observations within this range.

Notably, the highest observed snow depth (SD) in 2021 was 88.76 cm, while the average SD across 68 stations stood at 21.46 cm. Moving on to the evaluation of performance, the overall RMSE encompassing January 2021 to March 2021 registers at 39.27 mm. Moreover, the RMSE values for each individual month are calculated as 39.92 mm for January, 39.33 mm for February, and 38.02 mm for March, respectively.

**Table 1.** H65 validation results for January 2021 – March 2021 over Türkiye

| Range (mm) | H65 SWE (mm) | Ref. SWE (mm) | Std. Dev. (mm) | Mean Error (mm) | Data Count |
|---|---|---|---|---|---|
| **0-25** | 0.30 | 32.64 | 1.42 | -32.34 | 636 |
| **25-50** | 41.15 | 43.85 | 4.98 | -2.70 | 20 |
| **50-75** | 65.37 | 60.34 | 7.75 | 5.03 | 59 |
| **75-100** | 88.36 | 74.79 | 6.19 | 13.57 | 177 |
| **100-125** | 111.98 | 97.57 | 7.16 | 14.41 | 188 |
| **125-150** | 133.38 | 108.36 | 6.08 | 25.02 | 99 |
| **150-175** | 153.00 | 101.03 | 3.21 | 51.97 | 1 |
| **175-200** | 185.25 | 195.74 | 8.98 | -10.49 | 4 |

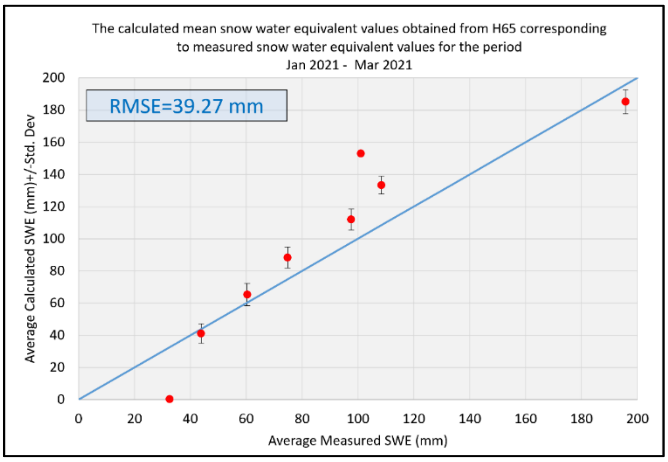


**Figure 5.** Average SWE of H65 in contrast to the average SWE derived from the in-situ dataset over Türkiye for January 2021 to March 2021

### 3.2 Validation Results over the U.S.

From a pool of 1,045,089 valid observations, the monthly RMSE metrics for January, February, and March of the year 2021 amount to 14.61 mm, 18.25 mm, and 12.77 mm, respectively (cf. Table 2). The overall RMSE of the H65 product is calculated as 15.19 mm.

As deduced from Table 2, the predominant dataset distribution is mainly concentrated within the interval of 0 to 25 mm SWE. Specifically, this encompasses 86.5% of the dataset. The visual representation given in Figure 6 depicts the H65 SWE dataset adhering closely to a consistent trajectory alongside the 1:1 reference line yet displaying a slight tendency to overestimate SWE values for intervals exceeding the 0 to 25 mm range.

**Table 2.** H65 validation results for January 2021 – March 2021 over the Conterminous U.S.

| Range (mm) | H65 SWE (mm) | Ref. SWE (mm) | Std. Dev. (mm) | Mean Error (mm) | Data Count |
|---|---|---|---|---|---|
| **0-25** | 1.26 | 4.12 | 4.40 | -2.86 | 904 670 |
| **25-50** | 36.74 | 25.92 | 7.18 | 10.82 | 66 980 |
| **50-75** | 60.91 | 43.33 | 7.07 | 17.58 | 40 760 |
| **75-100** | 86.65 | 66.37 | 6.92 | 20.28 | 20 972 |
| **100-125** | 110.58 | 99.68 | 6.87 | 10.90 | 9778 |
| **125-150** | 134.42 | 120.96 | 6.23 | 13.47 | 2078 |
| **150-175** | 156.87 | 133.27 | 6.94 | 23.60 | 224 |
| **175-200** | 187.07 | 159.67 | 8.23 | 27.40 | 27 |

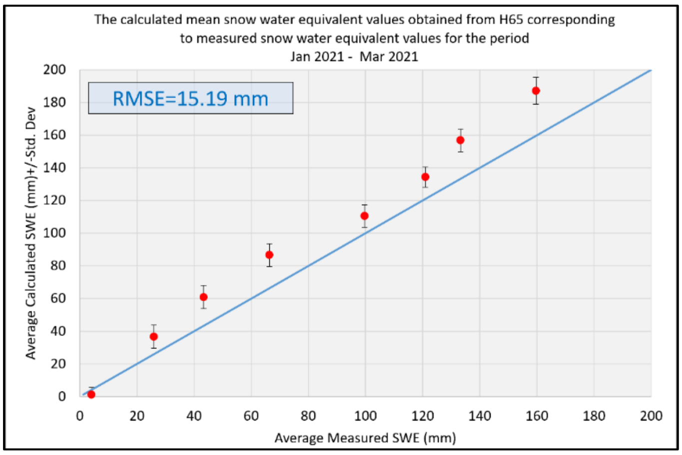


**Figure 6.** Average SWE of H65 in contrast to the average SWE derived from the 1-km U.S. SWE dataset for January 2021 to March 2021

This comprehensive evaluative analysis, spanning the expanse of the United States, stands as a compelling illustration aimed at appraising the performance attributes inherent to H65 SWE estimations. However, it is crucial to acknowledge that the reference data source employed in this study equally constitutes an assimilated SWE product, thereby inherently encompassing certain intrinsic inaccuracies, as indicated in the corresponding product user manual (Webster and Fetterer, 2004).

## 4. Discussions and Conclusions

The validation of satellite-derived snow products is of vital significance in ensuring the reliability and accuracy of remote sensing data in snow hydrology studies. In this study, we have assessed the H SAF H65 SWE product's performance over two geographically diverse areas: Türkiye and the conterminous United States. Through the utilization of in-situ SD measurements for validation in Türkiye and the 1-km gridded SWE product of SNODAS for the U.S., we aimed to establish the fidelity of the H65 SWE estimates. The significance of validating satellite-derived snow products lies in their potential to underpin various applications, including water resource management, climate modeling, and hazard assessment. The H65 SWE product, offering continental-scale coverage, presents a valuable tool in these contexts. Encouragingly, our validation results demonstrate that the product user requirements are met over both Türkiye and the U.S.

However, the task of validating a snow product with coarse spatial resolution is not without challenges. One of the main challenges encountered in this validation pertains to the representativeness of point-based in-situ measurements across the larger spatial footprint of a single pixel in the H65 SWE product. This is particularly evident in rugged mountainous regions, where the inherent variability of snow cover can be substantial even within a relatively small area. The elevation gradients, local topography, and microclimatic influences characteristic of such terrains can lead to discrepancies between point observations and the spatially integrated satellite measurements. The utilization of such point data as the sole validation reference for the H65 SWE product may therefore introduce uncertainties that require careful consideration. Another prominent challenge arises from the quest for suitable high-quality reference datasets, be they in-situ observations or alternative sources, as the 1-km gridded U.S. SWE dataset used in the study. The scarcity, spatial distribution, and temporal variability of such reference datasets require careful selection and calibration, increasing the complexity of the validation process. The gridded snow depth, snow water equivalent data set is needed for Türkiye, since the limited number of ground observations at high altitudes.

Furthermore, in the conterminous United States, the validation process encountered the challenge of reconciling the higher spatial resolution of the SNODAS gridded product with the coarser resolution of the H65 SWE estimates. The comparison of these datasets necessitates robust methodologies to ensure meaningful results, considering the potential biases introduced by the differences in spatial scales, as well as the intrinsic error sources of the model/satellite-derived reference datasets.

Our validation efforts produced compelling results, with an overall RMSE of 39.27 mm for Türkiye and a notably lower RMSE of 15.19 mm for the United States. These findings are of paramount importance, as they directly align with the product requirement thresholds, set at 40 mm for flat areas, thus establishing the H65 SWE product as a dependable resource for flat terrains in Türkiye. In the United States, where the RMSE is well below the threshold for flat areas, this product shines in terms of precision. Furthermore, in both regions, the product comfortably meets the requirement threshold for mountainous areas, set at 45 mm, underscoring its reliability for such complex terrains.

For broader-scale applications such as climate monitoring and hydrological modeling, the results may indeed be deemed satisfactory. These applications often encompass larger spatial scales, where the observed RMSE values fall within an acceptable range. The H65 SWE product's compliance with product requirement thresholds for both flat and mountainous areas in Türkiye and the United States reaffirms its viability for such purposes. Moreover, it's crucial to acknowledge that the H65 SWE product's performance could vary temporally and spatially. Seasonal variations and differences in terrain characteristics can influence the product's accuracy. Therefore, when considering the suitability of these results for specific applications, one must consider the particular context and spatial and temporal scales of the application.

In conclusion, this study contributes to the understanding of the H65 SWE product's performance across varying geographical contexts. The validation process underscores the necessity of accounting for the limitations inherent in both satellite products and ground-based observations. Future advancements in validation methodologies should consider incorporating spatial disaggregation techniques and statistical analyses that account for the complexities of different landscapes. Such endeavors are important in enhancing the credibility of satellite-derived snow products and furthering their applicability in hydrological and environmental studies. In parallel, EUMETSAT H SAF's contributions in the field of satellite-derived snow products underline the importance of collaborative efforts in advancing scientific understanding. H SAF's quest to develop accurate and reliable snow products has provided a platform for multidisciplinary research and operational practices.

## References


Breen, C., Vuyovich, C., Odden, J., Hall, D., Prugh, L., 2023. Evaluating MODIS snow products using an extensive wildlife camera network. Remote Sensing of Environment 295, 113648.

Carroll, T., Cline, D., Fall, G., Nilsson, A., Li, L., Rost, A., 2001. NOHRSC Operations and the Simulation of Snow Cover Properties for the Conterminous U.S. In, The 69th Annual Meeting of the Western Snow Conference, National Operational Hydrologic Remote Sensing Center, National Weather Service, NOAA, Minnesota, US.

H-SAF_H13_PUM, 2018. Product User Manual (PUM) for product H13 – SN-OBS-4 Snow water equivalent by MW radiometry. https://hsaf.meteoam.it/Products/Detail?prod=H13, Accessed on 30 August 2023.

Hall, D.K., Riggs, G.A., Salomonson, V.V., 1995. Development of Methods for Mapping Global Snow Cover Using Moderate Resolution Imaging Spectroradiometer Data. Remote Sensing of Environment 54, 127-140.

Kuter, S., Akyurek, Z., Weber, G.W., 2018. Retrieval of fractional snow covered area from MODIS data by multivariate adaptive regression splines. Remote Sensing of Environment 205, 236-252.

Kuter, S., Karaman, Ç.H., Akpınar, M.B., Akyürek, Z., 2022. Validation of EUMETSAT H-SAF space-born snow water equivalent product (H13) for the 2020-2021 snow year over Turkey. Anadolu Orman Araştırmaları Dergisi 8, 16-21.

Margulis, S.A., Fang, Y., Li, D., Lettenmaier, D.P., Andreadis, K., 2019. The Utility of Infrequent Snow Depth Images for Deriving Continuous Space-Time Estimates of Seasonal Snow Water Equivalent. Geophysical Research Letters 46, 5331-5340.

NSIDC, 2023. Summary of SMMR, SSM/I, and SSMIS Sensors http://rain.atmos.colostate.edu/FCDR/Archive_Docs/SSMIS_general/NOAA_STAR_SSMIS_TDR_CalVal_User_Manual.pdf, Accessed on 15 September 2023 2023.

Painter, T.H., Dozier, J., Roberts, D.A., Davis, R.E., Green, R.O., 2003. Retrieval of subpixel snow-covered area and grain size from imaging spectrometer data. Remote Sensing of Environment 85, 64-77.

Painter, T.H., Rittger, K., McKenzie, C., Slaughter, P., Davis, R.E., Dozier, J., 2009. Retrieval of subpixel snow covered area, grain size, and albedo from MODIS. Remote Sensing of Environment 113, 868-879.

Pulliainen, J., 2006. Mapping of snow water equivalent and snow depth in boreal and sub-arctic zones by assimilating space-borne microwave radiometer data and ground-based observations. Remote Sensing of Environment 101, 257-269.

Pulliainen, J., Hallikainen, M., 2001. Retrieval of Regional Snow Water Equivalent from Space-Borne Passive Microwave Observations. Remote Sensing of Environment 75, 76-85.

Saberi, N., Kelly, R., Flemming, M., Li, Q., 2020. Review of snow water equivalent retrieval methods using spaceborne passive microwave radiometry. International Journal of Remote Sensing 41, 996-1018.

Sorman, A.U., Beser, O., 2013. Determination of snow water equivalent over the eastern part of Turkey using passive microwave data. Hydrological Processes 27, 1945-1958.

Takala, M., Luojus, K., Pulliainen, J., Derksen, C., Lemmetyinen, J., Kärnä, J.-P., Koskinen, J., Bojkov, B., 2011. Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements. Remote Sensing of Environment 115, 3517-3529.

Tekeli, A.E., Akyürek, Z., Şorman, A.A., Şensoy, A., Şorman, Ü., 2005. Using MODIS snow cover maps in modeling snowmelt runoff process in the eastern part of Turkey. Remote Sensing of Environment 97, 216-230.

Viviroli, D., Dürr, H.H., Messerli, B., Meybeck, M., Weingartner, R., 2007. Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resources Research 43.

Webster, K., Fetterer, F., 2004. National Operational Hydrologic Remote Sensing Center. *Snow Data Assimilation System (SNODAS) Data Products at NSIDC, Version 1* [SWE]. Boulder, Colorado USA. https://nsidc.org/sites/default/files/g02158-v001-userguide_2_1.pdf, Accessed on 1 August 2023.